

## Popular Summary for

“Initial Performance Assessment of CALIOP,”

by

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The primary payload onboard the Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) satellite is a dual-wavelength backscatter lidar, called CALIOP, designed to provide vertical profiling of clouds and aerosols. Launched in April 2006, the first data from this new satellite was obtained in June 2006. The CALIOP lidar generates a 2-dimensional cross-sectional view of the atmosphere, revealing the vertical structure of clouds and aerosols. Data from CALIOP will be used by researchers to study, among many other subjects, the global heating or cooling effects of clouds, the influence of dust and pollutants on cloud development, and seasonal variability in cloud cover.

This paper is comprised of three distinct sections. The first provides an overview of the CALIPSO mission, placing the mission in the context of NASA science goals. The second describes technical details of the CALIOP lidar. The third presents initial measurement results including a brief discussion of validation measurements that were made to ensure accuracy of the CALIOP data. The measurements are shown to match expected performance limits.

1                                   **Initial Performance Assessment of CALIOP**

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9   The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP, pronounced the same  
10 as “calliope”) is a spaceborne two-wavelength polarization lidar that has been acquiring  
11 global data since June 2006. CALIOP provides high resolution vertical profiles of  
12 clouds and aerosols, and has been designed with a very large linear dynamic range to  
13 encompass the full range of signal returns from aerosols and clouds. CALIOP is the  
14 primary instrument carried by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite  
15 Observations (CALIPSO) satellite, which was launched on April, 28 2006. CALIPSO  
16 was developed within the framework of a collaboration between NASA and the French  
17 space agency, CNES. Initial data analysis and validation intercomparisons indicate the  
18 quality of data from CALIOP meets or exceeds expectations. This paper presents a  
19 description of the CALIPSO mission, the CALIOP instrument, and an initial assessment  
20 of on-orbit measurement performance.

21

## 1    **1. Introduction**

2    Aerosols and clouds play important roles in the Earth's radiation budget, in the  
3    hydrologic cycle, and have impacts on air quality. The CALIPSO mission was developed  
4    to provide global profiling measurements of cloud and aerosol distribution and properties  
5    to complement current measurements and improve our understanding of weather and  
6    climate (Winker, et al., 2003). CALIOP, the primary instrument carried by CALIPSO, is  
7    the first satellite lidar optimized for aerosol and cloud measurements and is also the first  
8    polarization lidar in space. CALIOP is based on a Nd:YAG laser operating at 1064 nm  
9    and 532 nm. The outgoing laser beam is linearly polarized and two polarization-sensitive  
10    532 nm receiver channels provide measurements of the degree of linear polarization of  
11    the return signal. Using the two 532 nm receiver channels and a channel measuring the  
12    total 1064 nm return signal, CALIOP measures the detailed vertical distribution of  
13    aerosols and clouds along with their microphysical and optical properties. Measurements  
14    of signal depolarization allow the discrimination of spherical and non-spherical cloud and  
15    aerosol particles (Sassen, 1991). Two-wavelength signals provide qualitative information  
16    on particle size and aid in discrimination of cloud and aerosol and the identification of  
17    aerosol type.

18  
19    The lidar technique provides direct measurements of range so it provides the most  
20    detailed and accurate information on cloud and aerosol height. CALIOP is also more  
21    sensitive to weak aerosol layers and thin clouds than passive satellite instruments, and so  
22    complements the information gained from existing satellites. CALIPSO flies as part of  
23    the "A-train" constellation of satellites, providing numerous measurement synergies with

1 the CloudSat cloud profiling radar and the various passive instruments of the A-train  
2 making cloud and aerosol measurements (Stephens et al., 2002). Observations from  
3 CALIOP will ultimately be used to improve the representation of aerosols and clouds in  
4 models used for climate prediction, weather forecasting, and air quality.

5

## 6 **2. Instrument Description**

7 The CALIOP transmitter includes two fully redundant Nd:YAG lasers. Only one is used  
8 at a time. Each laser produces simultaneous, co-aligned, pulses at 1064 nm and 532 nm.  
9 The lasers generate 20 nsec pulses at 1064 nm. A frequency doubling crystal converts  
10 roughly half this energy to 532 nm producing, nominally, 110 mJ of energy at each of the  
11 two wavelengths. Energy monitors measure the output pulse energy at each wavelength  
12 before expansion. A beam expander reduces the angular divergence of the transmitted  
13 laser beam to produce a beam diameter of 70 meters at the Earth's surface. The laser  
14 pulse repetition frequency of 20.16 Hz produces footprints every 333 m along the ground.  
15 The instrument operates continuously, providing observations during both day and night  
16 portions of the orbit.

17

18 Backscatter signals are collected by a 1-meter diameter telescope, sampled by analog  
19 detectors, and then digitized. A field stop at the focus of the telescope defines the  
20 receiver field of view of 130  $\mu$ rad (full angle) and provides rejection of background  
21 sunlight. An etalon with a passband of 35 pm is used in combination with a dielectric  
22 interference filter in the 532-nm channel to further reduce the solar background, while an  
23 interference filter alone is sufficient for the 1064 nm channel. The outgoing laser pulses

1 are linearly polarized with a purity greater than 99%. A polarization beamsplitter is used  
2 to separate components of the 532 nm return signal polarized parallel and perpendicular  
3 to the plane of the outgoing beam. A depolarizer located ahead of the beamsplitter can be  
4 moved into the beam for relative calibration of the two 532 nm channels. An avalanche  
5 photodiode (APD) is used for detection in the 1064 nm channel. Photomultiplier tubes  
6 (PMTs) are used for detection at 532 nm as they provide large linear dynamic range and  
7 higher sensitivity than the APD. Dual 14-bit digitizers on each channel provide the 22-  
8 bit dynamic range required to encompass the full range of molecular, aerosol, and cloud  
9 backscattering encountered in the atmosphere.

10 The analog signals from each detector are digitized at 10 MHz (corresponding to a 15 m  
11 range interval). Instrument timing is controlled to begin sampling when the laser pulse  
12 reaches an altitude of 115 km. Detector signals between altitudes of 112 km and 97 km  
13 and between 80 km and 65 km, where the lidar return signal is insignificant, are averaged  
14 to measure the solar background and DC signal level. Only the samples acquired below  
15 40 km from the 532 nm channel (and 30 km for the 1064 nm channel) are downlinked as  
16 profile data. To reduce the telemetry bandwidth, samples are averaged onboard the  
17 satellite before downlinking according to the scheme shown in Table 1. Further details on  
18 the instrument and data acquisition are given in Winker, et al.. (2004).

19

### 20 **3. Mission Description**

21 CALIPSO was launched from Vandenberg AFB on 28 April, 2006 together with the  
22 CloudSat satellite. CALIPSO flies in formation with the EOS Aqua and CloudSat  
23 satellites as part of the NASA Afternoon Constellation, or A-train (Stephens et al., 2002).

1 All the satellites of the A-train are in a 705 km sun-synchronous polar orbit with an  
2 equator-crossing time of about 1:30 PM, local solar time, and a 16-day repeat cycle. The  
3 orbit inclination of  $98.2^\circ$  provides global coverage between  $82^\circ\text{N}$  and  $82^\circ\text{S}$ . The orbit is  
4 controlled to repeat the same ground track every 16 days with cross-track errors of less  
5 than  $\pm 10$  km.

6  
7 The CALIPSO satellite flies behind Aqua. To minimize changes in cloud and aerosol  
8 properties between observations by the two platforms, the along-track separation is  
9 controlled to be less than two minutes. The CALIPSO orbit is slightly inclined to that of  
10 Aqua so that CALIPSO is located 215 km to the east of Aqua when crossing the equator  
11 on the day side of the orbit. This was done so the CALIPSO footprint remains outside of  
12 the sunglint pattern seen by the Aqua-MODIS instrument. CloudSat is controlled to fly  
13 10-15 seconds ahead of CALIPSO and to overlap the CALIOP footprint with the  
14 footprint of the CloudSat radar.

15  
16 CALIPSO flies in a nadir-pointing attitude so that the CALIOP footprints nominally fall  
17 on the satellite groundtrack. The satellite attitude is controlled to point CALIOP  $0.3^\circ$   
18 from geodetic nadir in the forward along-track direction. This small off-nadir angle  
19 avoids strong specular lidar returns from still water (ponds, rivers).

#### 20 21 **4. On-orbit measurement performance**

22 CALIOP 'first light' occurred on 7 June 2006. As this is written, CALIOP has completed  
23 9 months of near-continuous operation, and initial assessments indicate excellent on-orbit

1 performance. Level 1 data products from CALIOP are the calibrated, geolocated profiles  
2 of total backscatter return at 532 nm and 1064 nm and the perpendicular component of  
3 the 532 nm backscatter return. These profiles of “attenuated backscatter” are calibrated  
4 but not yet corrected for attenuation. Figure 1 shows examples of each of these products  
5 acquired early in the mission. The figure shows a nighttime transect from northern  
6 Europe southward across Africa into the Atlantic Ocean west of South Africa. Inspection  
7 of the three panels illustrates some of the capabilities of CALIOP to observe aerosols and  
8 clouds.

9 High cirrus located over tropical Africa, reaching altitudes of 17 km, is seen in the center  
10 of the image. The cirrus backscatter signal strength is similar at both wavelengths, due to  
11 the relatively large size of the cirrus particles. The cirrus is strongly depolarizing and  
12 produces a significant signal in the perpendicular channel. Significant attenuation  
13 produces the vertical dark stripes seen underneath optically thick features. Water clouds  
14 located near the top of the dust layer around 20° N and a stratiform cloud deck near 25° S  
15 produce very strong return signals. All three CALIOP receiver channels were designed  
16 with a linear dynamic range large enough so that even these strong cloud returns remain  
17 on-scale.

18 Layers of desert dust are seen beneath and immediately to the north of the cirrus, over the  
19 Sahara Desert. Dust particles are relatively large and irregular, and so also produce  
20 strong signals in the 1064 nm and perpendicular channels. An extensive layer of smoke,  
21 originating from biomass fires in southern Africa, can be seen south of the equator.  
22 Unlike the Sahara dust, this aerosol is non-depolarizing and produces negligible signal in  
23 the perpendicular channel, and also scatters more weakly at 1064 nm than at 532 nm. It

1 can be seen that the aerosol north of about 25° N is also non-depolarizing and more  
2 weakly scattering at 1064 nm. In this case the aerosol is dominated by secondary aerosol  
3 originating from anthropogenic activity in Europe. CALIPSO Level 2 algorithms provide  
4 identification of aerosol and cloud layers, classify aerosol into several types, and classify  
5 clouds by ice/water phase (Vaughan, et al., 2004).

6  
7 Only one of the two lasers has been used to date during on-orbit operations. Figure 2  
8 shows the time history of pulse energy during on-orbit operations of this laser. Three  
9 small, sudden, drops in energy were seen after about 40, 80, and 250 days of on-orbit  
10 operation, superimposed on a very slow decreasing trend. The Nd:YAG slab in the laser  
11 is pumped by 192 laser diode bars. The magnitude of these three sudden drops is  
12 consistent with the sudden dropout of one diode bar, which is expected to cause the total  
13 pulse energy to decrease by about 1 mJ. These sudden drops were also seen during on-  
14 orbit operation of the GLAS lasers on the ICESat satellite (Abshire et al., 2002), and are  
15 expected. The laser output can be seen to be stable following each of these events. The  
16 overall long-term trend is in line with expectations based on lifetime testing, which  
17 indicate a three-year lifetime for each laser.

18  
19 Figure 3 shows an observed profile of 532 nm attenuated backscatter from the surface to  
20 40 km. The data has been averaged over about 24,000 shots to improve SNR and allow  
21 comparison with the signal predicted from a purely molecular atmosphere. Above 18 km  
22 the atmosphere is cloud-free and aerosol contributions to the signal are insignificant. In  
23 this region, the observed signal strength is about 30% greater than predicted by the



1 instrument performance model, probably due to an overestimate of optical transmission  
2 losses by the instrument performance model. The figure also illustrates that the response  
3 remains linear well into the region where the average signal is much less than one  
4 photoelectron per range bin. SNR measurements made soon after launch gave values that  
5 were above the predicted values for all three channels, both day and night, and were at  
6 least 50% above requirements. Later measurements showed a drop of less than 10%  
7 over the first six months of operation, which is in line with expectations.

8

9 A number of aircraft underflights have been conducted for validation of CALIPSO  
10 measurements. Figure 4 shows results from a nighttime validation flight conducted on 11  
11 August, 2006 where the Cloud Physics Lidar (CPL) (McGill et al., 2002) was flown on  
12 the NASA ER-2 along the CALIPSO ground track. The CPL operates at the same two  
13 wavelengths as CALIOP and has polarization capability at 1064 nm. The upper and  
14 lower panels show profiles of an extensive cirrus deck acquired by CALIOP and CPL,  
15 respectively. Below the cirrus deck, at about 5 km, the tops of stratiform clouds are seen  
16 and in the right half of the figure the stratiform clouds become optically thin so that the  
17 lidar profiles extend to the surface. On this flight, the cross-track error between the ER-2  
18 and the CALIOP footprint locations was less than 500 m, and the similarity of the cloud  
19 features is evident. The time of exact temporal coincidence is indicated by the vertical  
20 line. Due to the different velocities of the two platforms, the CALIOP image represents  
21 30 seconds of data acquisition while CPL required nearly 17 minutes to cover the scene.  
22 The comparison shows generally good agreement between the two instruments in terms  
23 of sensitivity, spatial details, and signal calibration. One artifact that has been noticed in

CALIOP 532 nm returns from strongly scattering targets is a delayed recovery from the large transient signal. This behavior is due to the particular PMT detectors used and is not seen in the 1064 nm channel. This artifact can be seen in the comparison of returns from the stratiform cloud near 5 km and from the surface in the two panels of Figure 4.

## 5. Summary

CALIOP is the first polarization lidar to fly in space and has been acquiring unique observations of aerosols and clouds since June 2006. Initial validation intercomparisons have been performed and preliminary data products are now available through NASA Langley Atmospheric Sciences Data Center (ASDC). Descriptions of data products can be found in Vaughan et al. (2004) and are also posted on the ASDC web site. Quantitative analyses of CALIOP data are now underway. In addition to new insights which will come from CALIOP data used alone, combining data from CALIOP with coincident observations from other A-train instruments will allow numerous measurement synergies to be realized.

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Table 1. Spatial resolution of downlinked data.

<u>Altitude Range (km)</u>	<u>Horizontal Resolution (km)</u>	<u>532 nm Vertical Resolution (m)</u>	<u>1064 nm Vertical Resolution (m)</u>
30.1 to 40.0	5.0	300	---
20.2 to 30.1	1.67	180	180
8.2 to 20.2	1.0	60	60
-0.5 to 8.2	0.33	30	60
-2.0 to -0.5	0.33	300	300

## Figure Captions

Figure 1. CALIOP observations on June 9, 2006, acquired along an orbit track from northern Europe across Africa into the south Atlantic. The three panels show lidar return signals (attenuated backscatter) from the three CALIOP channels, calibrated in units of  $\text{km}^{-1}\text{sr}^{-1}$ . Shown are total 532 nm return (upper panel), 532 nm perpendicular return (middle panel), and total 1064 nm return (bottom panel). Strong returns from clouds and from the surface appear in grayscale. Yellows and reds represent weak cloud and strong aerosol scattering, and greens and blues represent molecular scattering and scattering from weak aerosol and cloud layers.

Figure 2. Laser pulse energy history during on-orbit laser operations, through March 15, 2007.

Figure 3. Observed average 532 nm return signal (solid line) and predicted molecular signal (dashed line).

Figure 4. Coincident nighttime data from the 532 nm channels of CALIOP (upper panel) and CPL (lower panel) acquired on 11 August 2006. The vertical line indicates the location of exact temporal coincidence.

## Figures

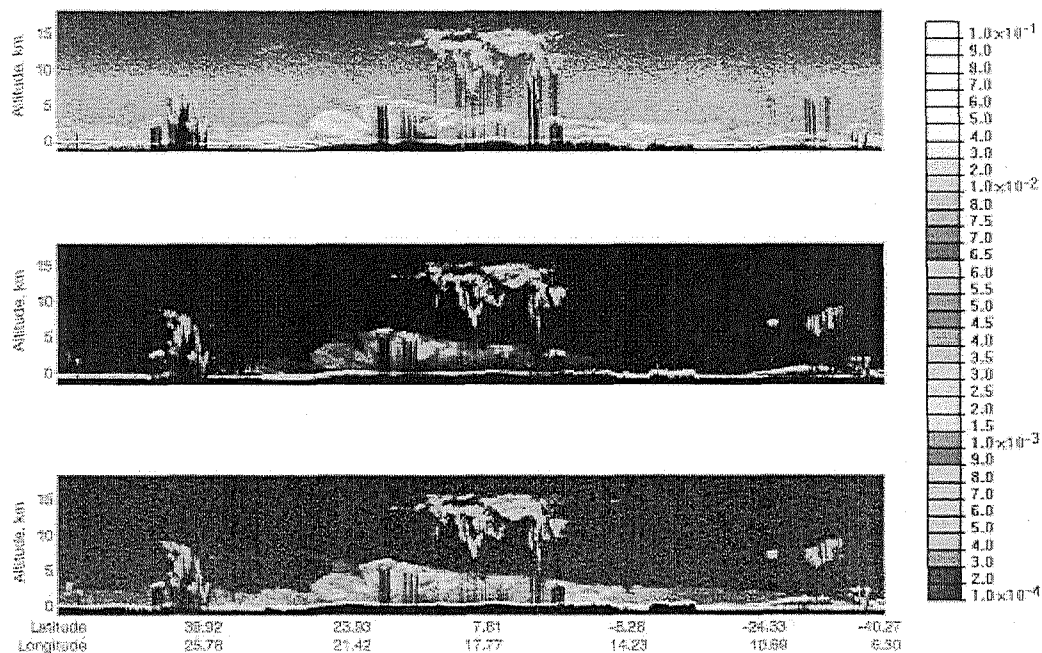


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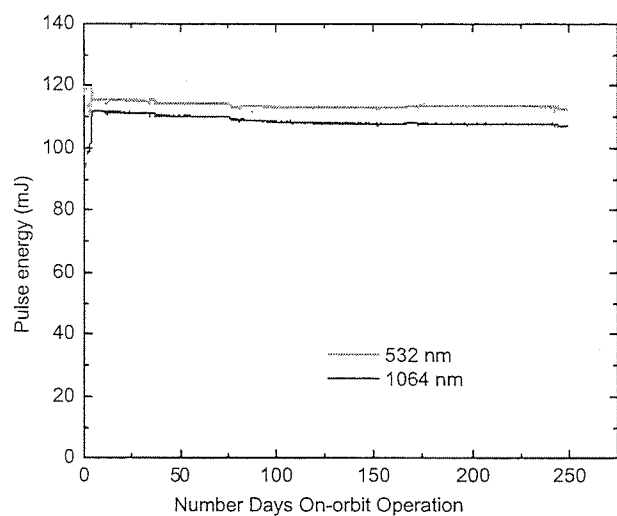


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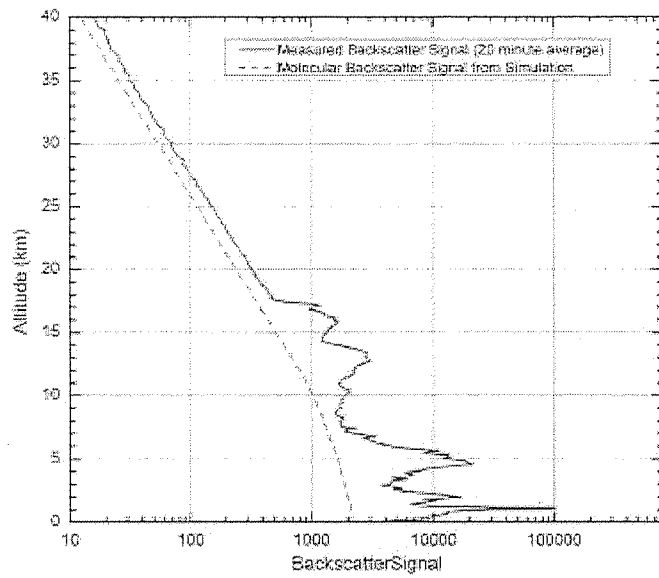


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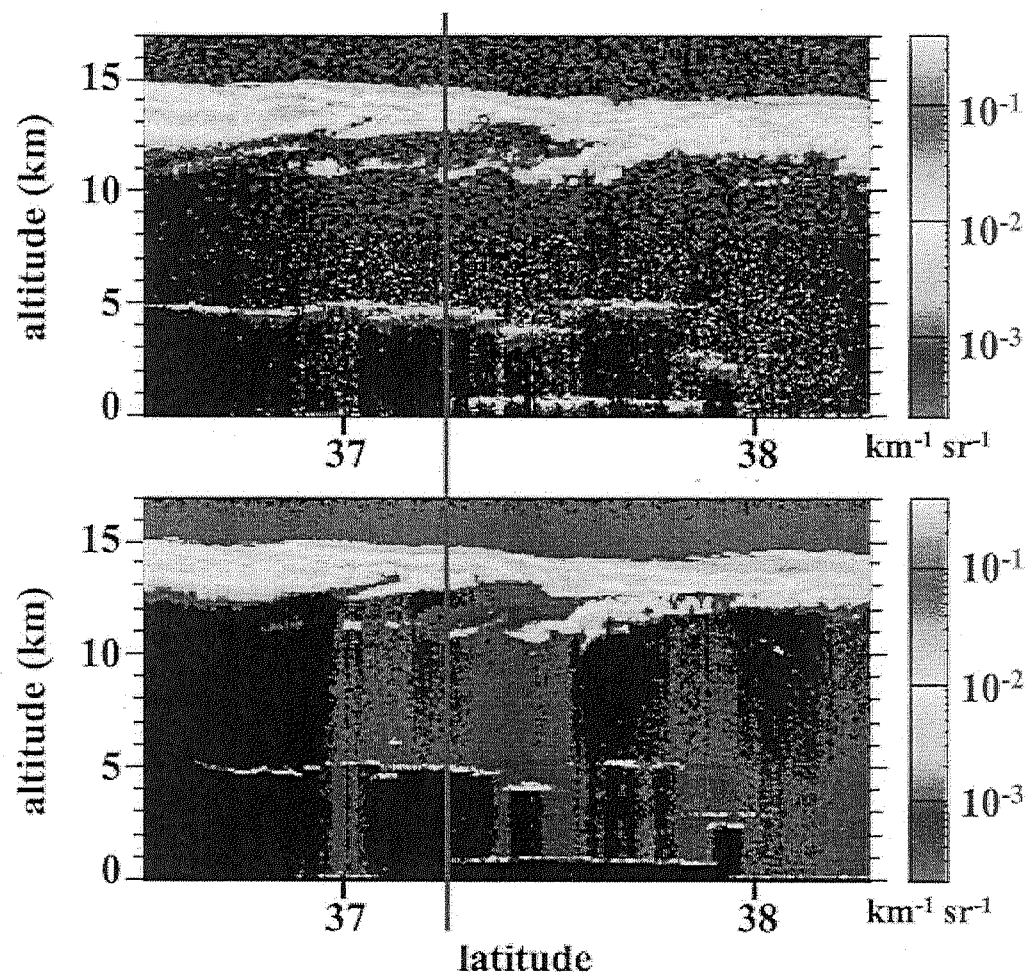


Figure 4. Coincident nighttime data from the 532 nm channels of CALIOP (upper panel) and CPL (lower panel) acquired on 11 August 2006. The vertical line indicates the location of exact temporal coincidence.